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Quenched KS light hadron mass at $\beta = 6.5$ on a 64×48^3 lattice*

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We report our quenched staggered light hadron mass calculation at the coupling of $\beta = 6.5$ on a $48^3 \times 64$ lattice, based on an increased statistics of two hundred gauge configurations. Staggered quark wall sources with mass of $m_q a = 0.01, 0.005, 0.0025$ and 0.00125 are used. Flavor symmetry is restored for pion and ρ meson. The lattice scale is estimated to be $a^{-1} = 3.7(2)$ GeV.

We report our light hadron mass calculation in quenched lattice quantum chromodynamics (QCD) with an increased statistics of two hundred gauge configurations. Our lattice size is $48^3 \times 64$ and the inverse-squared coupling is $\beta = 6.5$. Staggered quark wall sources of quark mass $m_q a = 0.01$, 0.005, 0.0025 and 0.00125 and point sink are used. These parameters roughly correspond to a physical box of $(2.4\ \mathrm{fm})^3$ and lattice cut off of $a^{-1} \sim 4$ GeV [1].

The space-like lattice size of 48 allows efficient use of a 24-node partition of the RIKEN's 30-node VPP500/30 vector-parallel supercomputer. In generating the gauge configurations we use a combination of a Metropolis update sweep followed by an over-relaxation one. The separation between two successive hadron-mass calculations is 1000 such pairs of sweeps and take about 3 hours in total including the necessary disk accesses. This separation should be about equivalent with a series of earlier studies at lower cutoff or smaller volume [3]. With the current statistics of 200 configurations the autocorrelation in successive Nambu-Goldstone pion propagators at time $t = 20$ is about 15 %. All the configurations used for the hadron-mass calculations, almost 2 Gbytes each, are stored in a tape archive. This will enable us to study hadrons with strangeness and charm in the near future. Further details on our simulation method and characteristics were already reported [1,2].

We finished a covariant χ^2 analysis on our current 200 gauge configurations (see Table 1). Re-

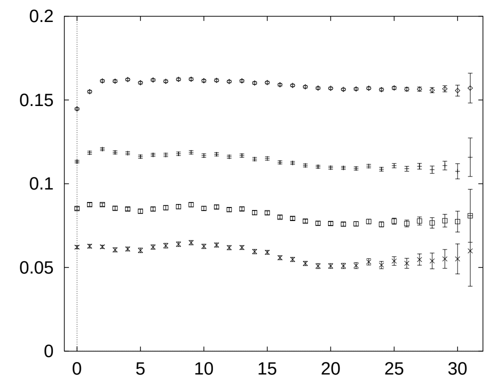

Figure 1. Nambu-Goldstone pion effective mass at $\beta = 6.5$ on $48^3 \times 64$ lattice for quark mass $m_q = 0.01$, 0.005, 0.0025 and 0.00125. Corner-wall source. The errors are estimated by Jackknife method.

sults of two fitting methods are summarized in the table. Fit (1) uses the same procedure as in the previous studies [3]: minimize the correlated χ^2 function and choose the best fit by following the maximum of (degrees of freedom) $\times$ (confidence) / (error). Fit (2) uses the same quantity but choose from plateaus in later time but before the signal disappears. The reason why we include these two fits are discussed in the following.

Let us look at the effective mass of Nambu-Goldstone pion plotted in Figure 1. At a first glance, we observe nice long plateaus with small error bars: if we neglect first four or five points in

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time, the remaining points seem to align on a well defined plateau for each quark mass. Indeed if we take weighted average of the effective mass from $t = 5$ through 31, we get pion mass estimates of 0.1592(4), 0.1135(7), 0.0812(8) and 0.0583(9) for the four quark mass values of 0.01, 0.005, 0.0025 and 0.00125 respectively. However, closer inspection of Figure 1 reveals strange wiggles and there seem to be two plateaus for each quark mass: one for a higher mass in earlier time and the other for a lower mass in later time. This tendency is more pronounced for lighter quark mass cases. After we apply the same procedure for globally fitting the pion propagator as in ref. [3] (*ie* fit(1)), we are led to higher mass estimates of 0.1618(4), 0.1170(5), 0.0856(8) and 0.0634(9) from the best correlated χ^2 for $t \leq 14$. If we choose lower plateau region and neglect the first plateau (*ie* fit(2)), we get estimates of 0.1575(3), 0.1109(4), 0.0767(7) and 0.052(1) for $t \geq 16$.

Both earlier and later plateaus may have problems. The earlier one can be contaminated by unwanted excited states. The later one can be dominated by noise, which usually lightens the fitted mass. Or perhaps the wiggles arise from intrinsic nature of effective mass [4]. Thus we are trying various different procedures in extracting light hadron mass from the propagators. In particular in fit (3), we fit Jack-knife effective mass from farthest possible time towards earlier time till the χ^2 begins to diverge. As we noted, fit (1) tends to give the earliest possible plateau in each channel, and thus may suffer from unwanted excited state contribution. Fit (2) tends to give later plateau and maybe free from such excited state but noise may come in since we are far out in time. Fit (3) should be also free from excited states, but does not work well unless the Jack-knife errors are well controlled. With our current statistics, fit (3) works at least for π and π_2 and gives their mass estimates that agree with fit (2).

We are also worried about whether the autocorrelation time is longer than expected. We are accumulating more statistics. In addition to the current 200 gauge configurations, we have so far accumulated 82 more configurations with twice larger separation (2000 pairs of Metropolis and over-relaxed sweeps). In a preliminary analysis,

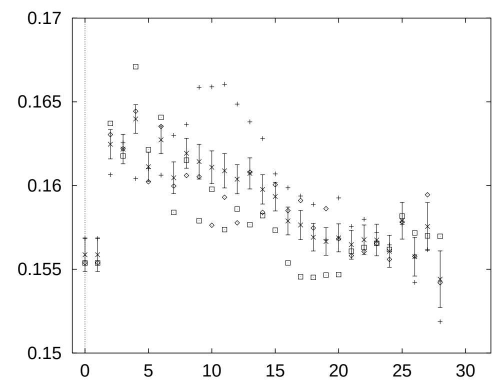

Figure 2. Effective mass of pion calculated with 2000-sweep separation for quark mass $m_q = 0.01$. $\diamond$ is the effective mass from the first 50, $+$ is from the second 50, $\square$ is from the third 50, and $\times$ is from all 150.

we grouped our data into three 50-configuration sets. The current 200 configurations with 1000 sweep separations is reduced to 100 configurations by taking every other one and then divided into two, earlier and later, 50-configuration groups. We also take 50 configurations from 2000-sweep runs and make it the third group. With these three groups, we calculated effective mass for pions. See Figure 2 for the $m_q = 0.01$ result. We see the effective mass from each 50-configuration set fluctuates around the value from the total 150 gauge configurations. In particular, the effective mass in the region typically selected by fit (1) shows large fluctuations. This suggests a longer autocorrelation time and our earlier autocorrelation analysis of the pion propagator could be misleading. We are currently investigating this by increasing statistics.

In Figure 3 we plot effective mass of flavor symmetry partners: Nambu-Goldstone pion π and non-Goldstone one π_2, ρ and ρ_2, and N_1 and N_2, for the heaviest quark mass value of 0.01. We clearly observe that π and π_2 are on top of each other, and so are ρ and ρ_2. The same is observed for pions and ρ mesons for the lighter

Table 1
Hadron mass at $\beta = 6.5$ on $48^3 \times 64$ lattice.

$m_q a$	particle	fit (1)		fit (2)	
0.01	π	3-14	0.1618(4)	16-26	0.1575(3)
	π_2	8-15	0.1594(6)	16-26	0.1604(6)
	σ	6-11	0.314(3)	8-15	0.318(3)
	ρ	10-16	0.2451(9)	15-24	0.239(1)
	ρ_2	10-15	0.244(1)	14-23	0.239(1)
	a_1	10-15	0.345(3)	14-23	0.343(6)
	b_1	10-16	0.348(4)	15-24	0.37(1)
	N_1	10-17	0.364(2)	15-24	0.354(3)
	N_2	5-13	0.340(1)	7-21	0.339(1)
	Δ	7-13	0.412(2)	11-17	0.404(3)
0.005	π	5-14	0.1170(5)	16-27	0.1109(4)
	π_2	6-15	0.1151(7)	10-21	0.1152(8)
	σ	6-15	0.311(6)	10-21	0.32(1)
	ρ	10-16	0.226(1)	15-24	0.218(2)
	ρ_2	10-16	0.222(2)	14-21	0.216(2)
	a_1	10-16	0.320(5)	14-23	0.32(1)
	b_1	10-16	0.328(7)	12-27	0.33(1)
	N_1	8-20	0.327(3)	10-20	0.321(3)
	N_2	5-13	0.301(2)	7-14	0.298(2)
	Δ	6-13	0.394(2)	12-17	0.372(5)
0.0025	π	8-14	0.0856(8)	18-23	0.0767(7)
	π_2	5-20	0.086(1)	14-21	0.0823(2)
	σ	4-20	0.294(7)	7-14	0.32(2)
	ρ	7-16	0.222(2)	10-16	0.218(2)
	ρ_2	8-19	0.217(2)	10-21	0.211(3)
	a_1	8-14	0.315(5)	10-19	0.306(8)
	b_1	7-16	0.326(7)	10-25	0.32(1)
	N_1	7-20	0.317(4)	8-20	0.308(5)
	N_2	4-15	0.281(2)	7-15	0.277(3)
	Δ	5-10	0.394(3)	8-14	0.370(5)
0.00125	π	8-13	0.0634(9)	18-23	0.052(1)
	π_2	3-13	0.066(2)	5-13	0.065(3)
	σ	4-13	0.28(1)	7-14	0.32(3)
	ρ	6-16	0.219(2)	10-25	0.215(4)
	ρ_2	4-10	0.227(3)	7-25	0.217(4)
	a_1	4-10	0.317(4)	8-20	0.302(9)
	b_1	5-17	0.321(7)	6-16	0.306(8)
	N_1	4-20	0.318(5)	6-23	0.314(7)
	N_2	4-15	0.271(4)	5-13	0.272(4)
	Δ	4-22	0.403(5)	6-25	0.376(5)

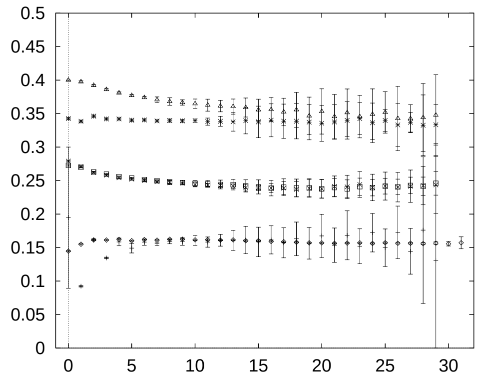

Figure 3. Effective mass of flavor symmetry partners at $\beta = 6.5$ on $48^3 \times 64$ lattice for quark mass $m_q = 0.01$: N_1 and N_2 (top), ρ and ρ_2 (middle) and π and π_2 (bottom). All show flavor symmetry restoration.

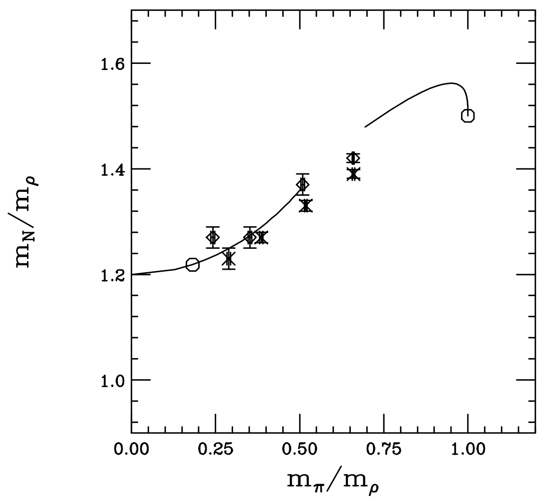

Figure 4. Edinburgh plot at $\beta = 6.5$ on $48^3 \times 64$ lattice for quark mass $m_q = 0.01$, 0.005, 0.0025 and 0.00125. The two different fits are plotted for each quark mass value.

quark mass values, 0.005, 0.0025 and 0.00125, albeit with more noise. From this we conclude that the flavor symmetry is restored in the present calculation. We also observe that N_2 signal, from the "even-point-wall" source, is nearly flat and N_1, from the "corner-wall" source, seems to converge with it for large t. Thus we will use N_2 for nucleon mass estimation.

Figure 4 gives the Edinburgh plot in which we included the data from fits (1) and (2). The errors in the figure are obtained by assuming that the relative error in each quantity is independent of each other.

Conclusions. We are close enough to the continuum to see flavor symmetry restored for both π and ρ. The lattice scale estimated by ρ mass at zero quark mass, $m_\rho(m_q = 0) = 0.21(1)$, is $a^{-1} = 3.7(2)$ GeV. An interesting Edinburgh plot is obtained, with m_π/m_ρ as small as 0.25 and m_N/m_ρ within the error bar of the experimental value. We still do not understand the systematic error associated with plateau selection in hadron effective mass. We plan to accumulate more statistics to study this. The answer to the question on the quenched chiral log in the pion mass m_π and chiral condensate $\langle\bar{\psi}\psi\rangle$ [5,6] should wait until we sort out this systematic error.

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